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BIOSPHERIC EFFECTS OF A LARGE EXTRATERRESTRIAL IMPACT: CASE STUDY OF THE CRETACEOUS/TERTIARY BOUNDARY CRATER

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Introduction

Alvarez and his colleagues[1] originally proposed that the large dust cloud from an asteroid or comet impact blocked out the sun and caused mass extinctions at the end of the Cretaceous. The recent recognition that the Chicxulub structure in northwestern Yucatan is this Cretaceous/Tertiary (K/T) impact site[2,3] allows us to refine the possible extinction mechanisms. A unique aspect of the Chicxulub crater is the presence of thick deposits of anhydrite ($CaSO_4$), which when impacted created a massive sulfuric acid aerosol cloud[4,5] that amplified environmental stresses beyond those proposed for the impact dust alone. The research undertaken by Geo Eco Arc Research and their collaborators in FY 1993 focussed on modeling of the impact and the atmospheric effects of the sulfuric acid aerosols produced. Additional research was conducted on the characterization of Chicxulub proximal ejecta deposits to provide imperical verification of the impact model.

Impact Modeling

The size of the Chicxulub crater is not well constrained. Estimates based primarily upon circular gravity anomalies indicate a diameter of ~180 km (ref 2) or 260-300 km (ref 6). Our analyses[7] of the crater geology indicate a rim diameter of ~240 km. We have obtained NASA airborne radar imagery (AIRSAR), and just recently NASA Shuttle Imaging Radar (SIR-C/X-SAR) imagery, of the crater to help resolve the issue of crater size. Nevertheless, given the

current uncertainties, we chose to model craters with diameters of 180 km and 300 km. We assumed a cylindrical silicate bolide impacting perpendicular to the surface at 20 km/s. More complex bolide geometries and oblique trajectories are difficult to model, and 20 km/s is a typical velocity for asteroids[8]. When scaling laws are applied[9] these diameters correspond to bolide diameters of about 10 km and 20 km for the two crater sizes. Recent studies[10] indicate that the Chicxulub impactor may have had a diameter as large as 32 km, hence our maximum estimate is conservative.

A sequence of carbonates and anhydrites ~2.5 km thick comprises the upper section of target rock near Chicxulub[11,12]. The sequence thickens to the northwest and the total thickness at the center of impact may be about 3 km. We used a 2D hydrocode impact model of a two layer target to estimate the anhydrite volume vaporized by the Chicxulub impact (Figure 1), from which we calculated shock pressures and the mass of sulfur vaporized (Table 1). We found that shock pressures rapidly decay near the surface due to a lack of confining pressure and a large volume of sediments are ejected without being vaporized.

The sulfur is released as SO_2 and SO_3 (refs 4,5,). A large volume of highly shocked (>100GPa) sediments lies directly beneath the bolide (Figure 1), and our model predicts that it is released to the atmosphere after decompression (~10 sec after impact). This "plug" of material may degas as SO_2. A smaller volume (~10-20%)

TABLE 1 Volume and Mass of Vaporized Material

Bolide Diameter km	Vaporized Sediments km^3	Sulfur Mass g	Baseline Sulfur Mass g
10	300-600	5.5×10^{16} - 2.3×10^{17}	10^{17}
20	1100-2000	2.0×10^{17} - 7.7×10^{18}	10^{18}

Impact model predictions of sediment volumes shocked >30 GPa (larger volume) and >100 GPa (smaller volume) for two possible Chicxulub bolide sizes (based on a sediment thickness of 3 km). We assume that complete vaporization of the anhydrites occurs within this range of shock pressures. The average anhydrite composition, as measured in exploratory oil wells near the crater rim[11], is 60%, however much of the stratigraphy in these wells is based on cuttings and geophysical data, which may overestimate anhydrite volume. To account for the variable estimates of anhydrite content, we use a range of anhydrite percentages in our model. Corresponding minimum sulfur masses are for 25% anhydrite in the sedimentary layer shocked >100 GPa, and maximum masses are for 50% anhydrite shocked > 30 GPa. Baseline sulfur masses used in atmospheric modeling bracket the minimum and maximum amounts of sulfur gas produced by the impact given that the actual amount of sediment vaporized lies between our minimum and maximum values.

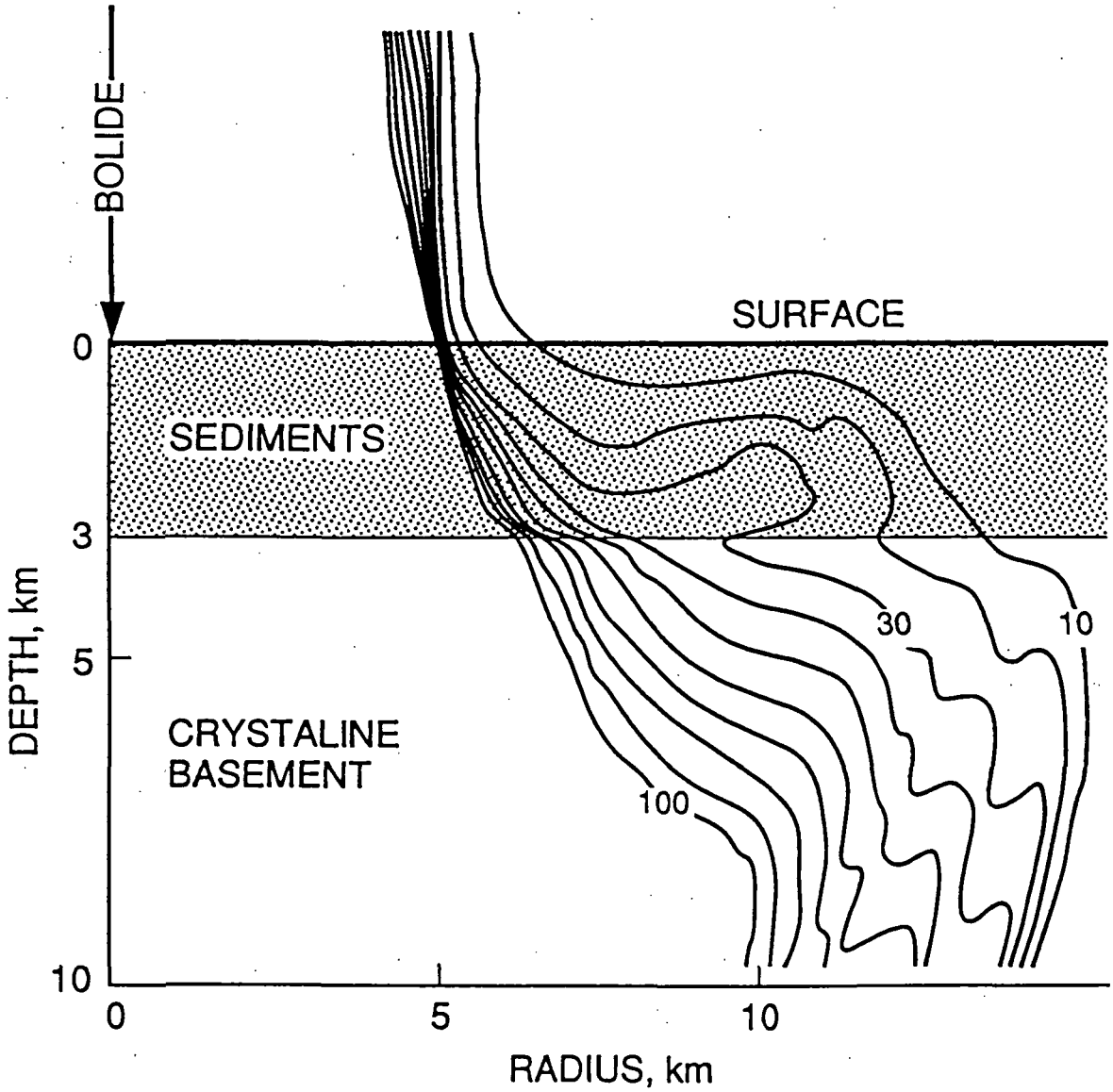

Figure 1. Results of impact model for the 10 km diameter bolide impact (right half only, shock pressure isobars in GPa). The top layer was modeled as a wet tuff, which corresponds to the 3 km thick sedimentary layer at Chicxulub, and the bottom layer as granite, which corresponds to the basement metamorphics in this region. Center of impact at arrow. Experiments and theoretical studies indicate that shock-induced vaporization of anhydrite occurs between 50-100 GPa under gas release pressures of 1 bar[34,35]. The theoretical studies indicate that vaporization can occur at lower shock pressures if the gas release pressures are less than 1 bar. Therefore we assume all sediments shocked >100 GPa are vaporized, and those shocked >30 GPa but <100 GPa are partially vaporized. Results of the 20 km diameter bolide impact are nearly identical, but with proportionally larger volumes of vaporized sediments. Computer code for impact simulation adapted from ref 36.

of the highly shocked sediments lies outside of the bolide footprint, and is released to the atmosphere rapidly. Laser experiments[13] that simulate impact processes in this zone indicate that more SO_3 than SO_2 is produced. Nevertheless, the heat generated by such a large impact favors the decomposition of the SO_3 to SO_2 in the plume[5]. The volatiles separate from the melt due to rapid gas expansion[14], and due to gravitational forces[5]. Previous models of K/T impact dynamics have shown that the plume extends beyond the stratosphere[15]. The global distribution of this highly shocked ejecta confirms that the dust cloud enveloped most of the Earth, and we assume that a globally distributed sulfur cloud formed in a very short time. Some of the sulfur may have recombined with the Ca rich oxides in the dust plume, but this was probably minor because of the mechanical separation noted above and because the lifetime of the dust was <6 months[16,17].

Atmospheric Modeling

We examined two possible scenarios for the massive release of sulfur to the stratosphere. The first is based on the assumption that the sulfur is rapidly converted to H_2SO_4 aerosol, which would occur if the dominant gas species is SO_3, or if chemical reactions in the plume produce H_2SO_4 directly. The second is based on the assumption that large quantities of SO_2 are produced, which must be oxidized by sunlight to form SO_3 prior to hydration to H_2SO_4. The two scenarios are not exclusive and both probably occurred.

We adapted a radiative transfer model originally designed for studies of planetary atmospheres[18] to the investigate the solar flux through the H_2SO_4 aerosol cloud. Our model calculates the amount of sunlight reaching the ground, both directly and diffusely through the cloud, based on Mie scattering theory.

Our first scenario involves coagulation and sedimentation. We adapted the coagulation model proposed in previous K/T impact studies[16], which is based on particle collisions due to Brownian motion and 100% cohesion. An initial mean particle size of 0.5 um was chosen based on Pinatubo volcanic H_2SO_4 aerosol studies[19]. We experimented with smaller sizes, but found that the model output is not very sensitive to smaller initial particles. The rapid formation of the H_2SO_4 aerosols permits acid nucleation on stratospheric dust and soot particles produced by the impact. Therefore our model examines the effect of impurities by using different imaginary indices of refraction.

The results of a series of model runs is shown in Figure 2. Model runs with larger aerosol loadings than the one shown produced lower transmission values at the outset, but did not prolong the effects. This self-limiting processes is well known for large volcanic eruptions[20]. Our results indicate that light levels dropped below the photosynthesis limit for 6-9 months if the acid droplets were slightly darkened by impurities.

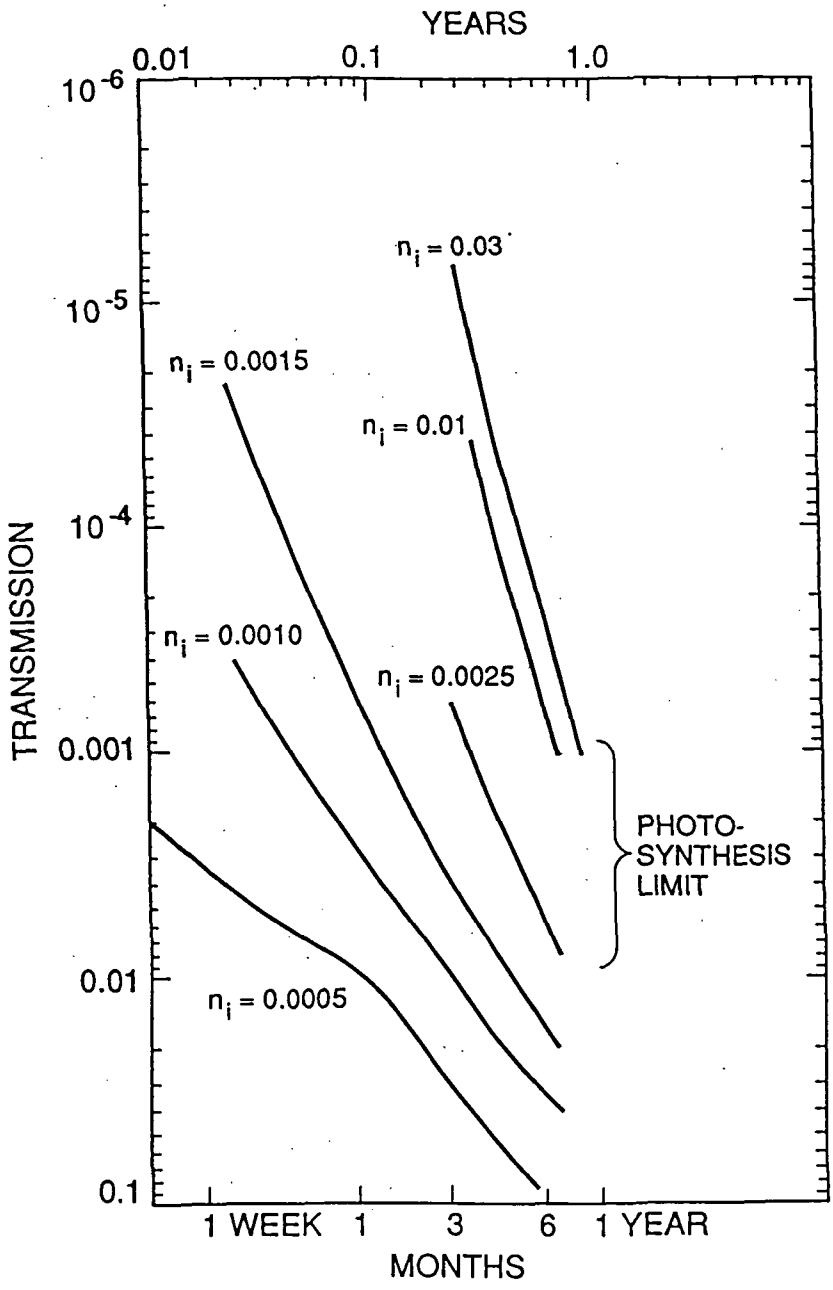

Figure 2. Reduction in solar transmission at the Earth's surface over time for an initial H_2SO_4 aerosol loading between 20 and 30 km of 5 x 10^{15} g of sulfur, which is equivalent to only 5% of our smaller baseline sulfur mass. Curves for different imaginary indices of refraction (n_i), which reflect possible impurities in the acid droplets. Soot n_i = 0.03; silicate dust n_i = 0.0025; pure H_2SO_4 aerosol n_i = 0.0005. Photosynthesis ceases when transmission drops below 0.001-0.01 (refs 15,37). Once particles fall below 10 km we assume that they are removed immediately by meteorological processes.

Our second scenario considers the SO_2 to H_2SO_4 aerosol conversion rate. This rate is about 10^{13} g/month for large volcanic eruptions, but it is proportional to the volume such that larger eruptions have faster rates[20]. Models of Venus[21] and Earth[20] indicate that the rate limiting factor is the photochemical oxidation of SO_2, which is controlled by the abundance of UV light and oxidants. The SO_2 lifetime for our larger baseline injection of SO_2, derived by scaling up volcanic conversion rates[20], is about 200 yrs. This rate is the same as that on Venus, which has approximately the same atmospheric sulfur concentration as our Chicxulub large baseline[22], which suggests such scaling is appropriate. Applying the same scaling to our small baseline yields an SO_2 lifetime of 50 yrs.

Our impact model indicates that the Chicxulub impact injected large amounts of water into the stratosphere, probably a mass within an order of magnitude of that of sulfur. This water may have increased the abundance of oxidants, but the effect on the oxidation rate would be minor because the abundance of oxidants varies with the square root of the water concentration and because oxidation is inhibited by the shielding of UV by the SO_2 cloud[20] (a factor accounted for in our SO_2 lifetime estimates). Oxidants may have ultimately become depleted, thus reducing the H_2SO_4 production rate and extending the lifetime of the SO_2 cloud.

Vertical diffusion of the SO_2 cloud also limits its lifetime. The SO_2 lifetime in today's lower stratosphere is about 2 yrs (ref 20). SO_2 from the Chicxulub impact would be originally deposited on top of the stratosphere and in such large abundances that it would take much longer than 2 yrs to diffuse to the troposphere and be removed. We used a diffusion e-folding time of 3 and 5 yrs to constrain the SO_2 lifetime.

The model results for both SO_2 baselines predict that solar transmission would drop to about 10% of normal for 12-26 yrs (Figure 3). This is equivalent to that of a very cloudy day, but above the photosynthesis limit. We calculated the corresponding surface equilibrium temperature changes (Figure 3), which are what would occur if the reduced solar flux lasted long enough for complete exchange of residual heat between the Earth's oceans, continents, and atmosphere, thus establishing a new equilibrium. Equilibrium temperatures dropped over 100^{o} C for our baseline sulfur masses, however actual temperature reductions would be less due to thermal buffering of the oceans.

Previous K/T impact models[16,17] predicted a 3-6 month blackout with freezing and disruption of photosynthesis due to the silicate dust. The rapid generation of H_2SO_4 aerosols may have slightly extended this blackout period to 6-9 months. Prolonged cooling is the important factor in the impact release of SO_2. Greenhouse global warming caused by CO_2 released from the vaporized carbonates

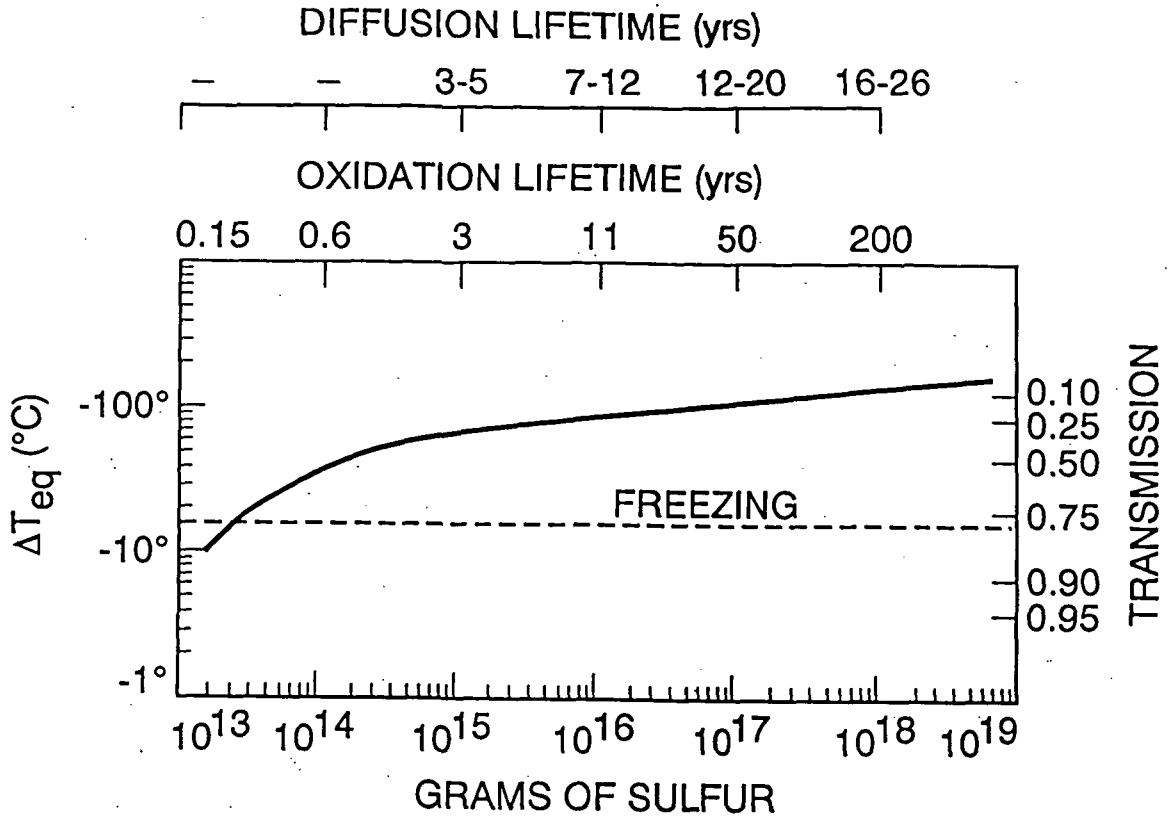

Figure 3. Model predictions for the reduction in solar transmission at the Earth's surface and corresponding change in surface equilibrium temperature (T_{eq}) for various SO_2 initial masses. Model is constructed such that the H_2SO_4 aerosol is continuously photochemically produced in the upper stratosphere. The lower stratosphere is effectively shielded from the sun, hence H_2SO_4 does not form at lower levels. Coagulation and sedimentation processes cause the aerosol particle size and number density to change as they fall, which were modeled in 12 stratospheric layers, the number of which was a compromise between limits on computational time and adequate characterization of changes in particle properties through the stratosphere. The resulting H_2SO_4 cloud properties represent quasi-steady-state conditions for the lifetime of the SO_2 cloud whereby new particles form in the first layer as those in the 12th layer fall below 10 km and are removed. Oxidation lifetimes are the time required to convert the given mass of sulfur into H_2SO_4 aerosol and are an integral part of the steady-state model. Diffusion lifetimes are the time required to remove sufficient unoxidized SO_2 by diffusion to the troposphere to shut down acid production (this process is insignificant for short oxidation lifetimes). For large sulfur masses the diffusion lifetime is the effective lifetime of the cloud. Once acid production ceases the aerosol cloud dissipates in about 1 year. Dashed line indicates transmission level at which the average global surface temperature would reach freezing, assuming equilibrium is reached and an initial average of 15° C. Actual temperature reductions would be buffered by heat released from the oceans for many years.

at Chicxulub may also be a factor[23]. The mass of CO_2 released approximates our maximum sulfur masses because carbonates vaporize at low shock pressures, thus causing $\leq 8^{o}$ C warming[23]. The climate forcing represented by this potential increase is insignificant compared to that represented by our proposed 100^{o} C cooling, however the residence time of CO_2 (50-200 yrs, ref 24) is greater than that proposed for the cooling event, and a century or more of warming may have followed the initial cooling.

Modeling of short-term impact-induced ocean cooling[25] suggests that significant cooling can occur in <14 years, but precise estimates of temperature changes remain uncertain due to poorly known Cretaceous ocean circulation patterns, which were probably much different from today's[26]. Nevertheless, given our conclusion of a prolonged reduction in solar flux, significant global cooling must have occurred within a few decades after the impact. Our models show that such cooling would occur even if the SO_2 produced was 10% of our minimum baseline, although then cooling would last only about a decade. Therefore, we hypothesize that continental regions were the most severely effected by the impact due to freezing. Coastal and island areas probably became temperate refugia for terrestrial biota, and survivors may have been species with access to the refugia and the ability to survive a prolonged period of constricted habitat.

Proximal Chicxulub Ejecta Studies

We recently dscovered a K/T boundary section in northern Belize that provides new insights into cratering processes near the rim of the Chicxulub crater and provides data for testing impact models. The section is located in a quarry on Albion Island near the Mexican border, which is only 2 to 3 crater-radii (~350 km) from the center of Chicxulub (Figure 4). This is the most proximal exposed K/T section yet studied from the Chicxulub crater, excluding material from deep drilling within the crater and on the rim. The Albion Island section provides an example of deposits intermediate between the crater rim and more distal, possible impact-tsunami deposits in the region[27,28,29].

Quarrying activity on Albion Island has exposed a 45 m thick section in a region where deep weathering and dense vegetation has obscured most bedrock exposures (Figure 5). The regional stratigraphy (Figure 5) has been established in two exploratory wells drilled at near by Orange Walk and San Pablo[30]. The Orange Walk 1 well records place the K/T boundary between dolomites of the Sand Hill Formation and undifferentiated Tertiary limestones at a depth of about 600 m. The K/T boundary rises to a depth of about 150 m in the San Pablo 1 well located 11 km north of Orange Walk 1. The Albion Island quarry is located 15 km northwest of Orange Walk, near the crest of an anticlinal fold and possible uplifted fault block that has further elevated the K/T boundary. A major

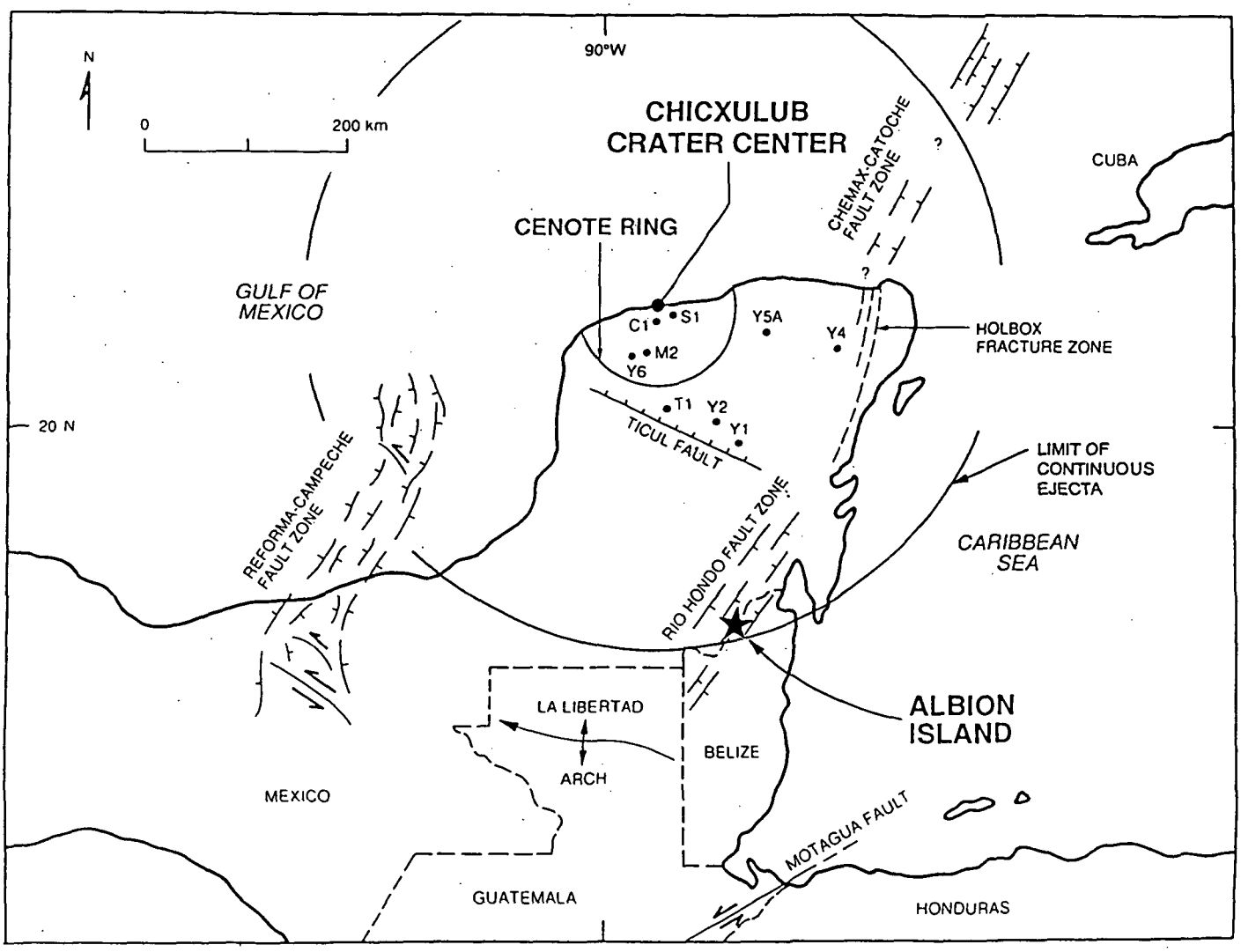

Figure 4. Location of Albion Island with respect to the Chicxulub Crater. Albion Island lies just within the theoretical limit of the zone of continuous ejecta (ballistic sedimentation) for a 300 km diameter crater.

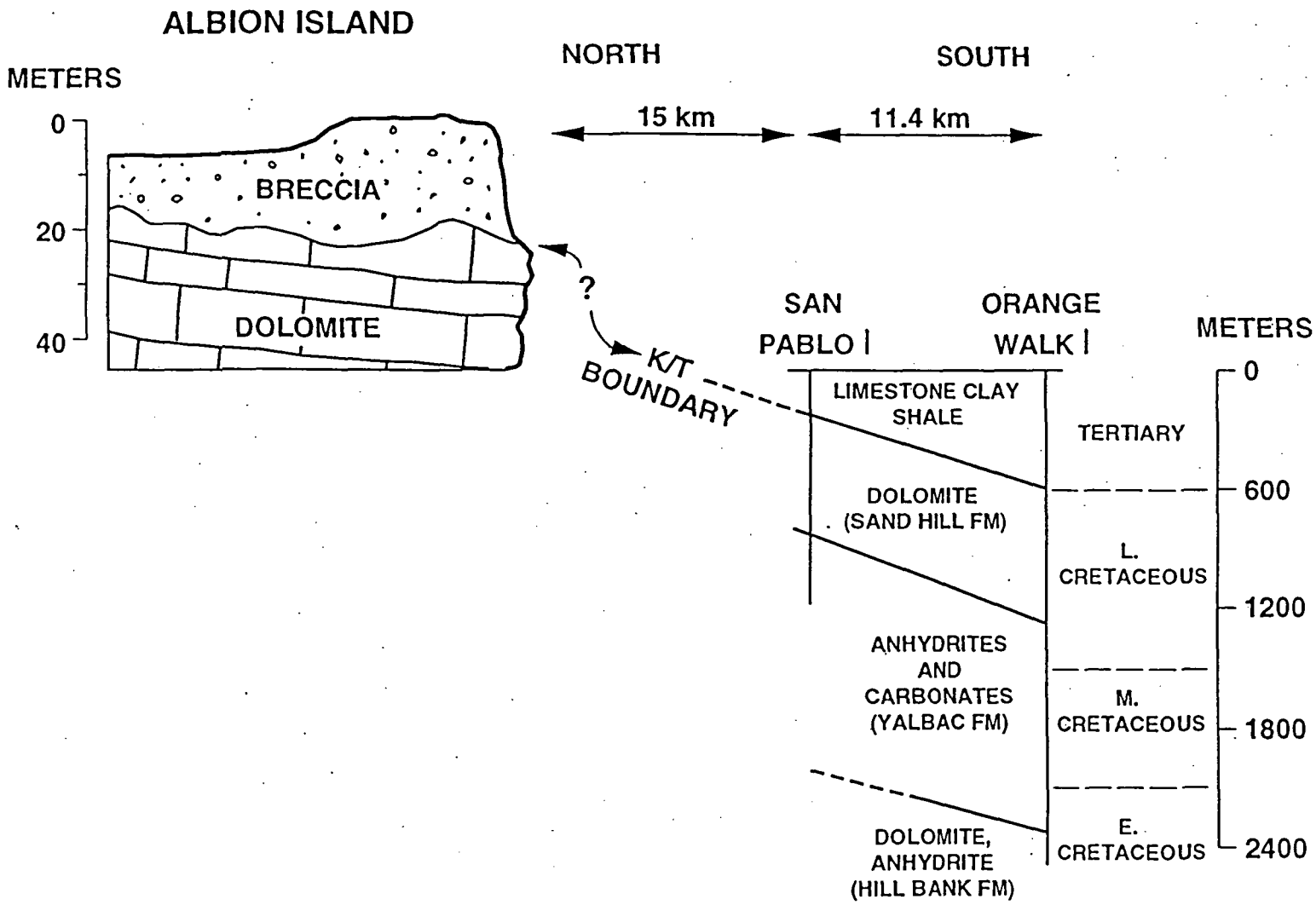

Figure 5. Stratigraphy of the Albion Island Quarry (upper left) and the regional stratigraphy of northern Belize from exploratory oil wells Orange Walk 1 and San Pablo 1.

erosional unconformity separates the hard crystalline Cretaceous dolomites and a chaotic, poorly sorted breccia at a depth of about 15 m in the quarry. We propose that this unconformity marks the K/T boundary.

The unconformity is exposed for a lateral distance of over 100 m and is parallel with the bedding planes in the underlying dolomites. It contains at least three erosional troughs that cut into the dolomites, each approximately 15 m wide and 2 m deep. The orientation of the troughs could not be determined, but they indicate high-energy scouring. The only sediments filling the scours are the chaotic breccias.

The maximum breccia thickness in the quarry is 15 m, however the breccias continue to the surface and the total original thickness of the unit is unknown. Tertiary strata are not exposed in the quarry, but are found on the surface in other parts of the island, presumably overlying the breccia. The breccia is weakly indurated and deeply weathered. Clasts range in size from 30 cm to microscopic grains, and all sizes are abundant. The clasts are angular to sub-rounded and supported in a dolomitic matrix. Most clasts, especially the large ones, are dolomite, apparently derived from the underlying beds. Other carbonate clasts, representing lithologies not found in the lower section, are also present. Some of the sub-rounded clasts are grain-supported, well indurated, and partially re-crystallized carbonate breccias. Highly altered

clasts consisting of red, green, and yellow clay are also abundant and give the unit a polychromatic appearance. The original lithology of these clasts was apparently glass as a single intact shard was found in acid leached samples. The shapes of the clay clasts, including angular, elongated, and often vesticular also suggests they were origianly glass. Quartz and grantic grains are present, but rare.

We propose that the Albion Island breccia is the product of ballistic sedimentation[31] from the Chicxulub impact. Such deposits are created by secondary impacts of ejecta and for large craters are composed mostly of brecciated local rock[32]. Impact models[31,33] predict that ballistic sedimentation would occur within 2-3 crater-radii of Chicxulub, consistent with the position of this K/T section. The breccia lithology and scoured contact are also consistent with the ballistic model, and the composition is remarkably similar to the breccia unit found in cores on the rim of the Chicxulub crater, which we have also interpreted as a product of ballistic sedimentation[7].

An important aspect of the Abion Island breccia is that the clasts are composed almost entirely of sedimentary rock. As noted above, many of these clasts appear to be local dolomites scoured from the surface by the ballistic sedimentation process. The exact percentage of local rock versus ejecta has not yet been determined, but the sedimentary clast lithology is highly variable, and

includes at least some verified Chicxulub ejecta. Our impact model predicts that a large volume of sedimentary rocks were ejected fron the crater without being vaporized. Future studies of the composition of the Albion Island Breccia will help contrain these model predictions.

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The Chicxulub Crater in Yucatan, Mexico is the primary candidate for the impact that caused mass extinctions at the Cretaceous/Tertiary boundary. The target rocks at Chicxulub contain 750-1500m of anhydrite ($CaSO_4$), which was vaporized upon impact, creating a large sulfuric acid aerosol cloud. In this study we apply a hydrocode modle of asteroid impact to calculate the amount of sulfuric acid produced. We then apply a radiative transfer model to determine the atmospheric effects. Results: 6-9 month period of darkness followed by 12-26 yrs of cooling.

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